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Investigations of Ventilation, Smoking Activity, and Indoor Air Quality at Four Large Office Buildings

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ABSTRACT

Four large office buildings were investigated to assess relationships among ventilation rate, smoking activity, and indicators of indoor air quality (IAQ). Two types of heating, ventilating, and air-conditioning (HVAC) systems were examined: induction-constant air volume (CAV) and variable air volume (VAV). Two types of smoking policy were examined: unrestricted smoking and smoking restricted to lounges where air was exhausted directly to the outdoors. The four buildings represented all combinations of these four variables. One floor of each building was investigated, with measurements conducted during the summer when HVAC systems were not in the economizer mode, so they used minimal amounts of outside air. Inspections of HVAC systems indicated that they were adequately designed, operated, and maintained. Ventilation rates for office spaces were measured by standard procedures based on velocity traverses. During the tests, all four systems provided ventilation rates essentially conforming to ASHRAE 62-1989. *For the two buildings where smoking was unrestricted, 34% of occupants were smokers; the average smoking rate was 1.6 cigarettes per smoker per hour. Indicators of air quality and environmental tobacco smoke (ETS) were determined in offices and in outside and return airstreams. IAQ indicators included respirable suspended particles (RSP), formaldehyde, volatile organic compounds (VOCs), carbon dioxide (CO_2), and carbon monoxide (CO). ETS indicators included ultraviolet particulate matter (UVPM), fluorescent particulate matter (FPM), and nicotine. Results show that (1) within the context of the current ASHRAE standard, smoking activity had a measurable, although negligible, effect on contaminant levels in buildings where smoking was unrestricted; (2) restricting smoking to lounges eliminated nonsmoker exposure to ETS by preventing smoke from dispersing to adjacent areas; and (3) with the HVAC systems adequately designed, operated in accordance with the current ASHRAE standard, and properly maintained, all indicators were below applicable standards, regardless of smoking policy.*

INTRODUCTION

The last decade has seen increasing emphasis on issues relating to the quality of the indoor environment. This emphasis stems in great part from the relatively large proportion of time people spend there. Our IAQ research program has included surveys to assess exposures to airborne contaminants, in general, and ETS, in particular, in various indoor microenvironments such as offices (Oldaker et al. 1990).

ASHRAE 62-1989, Ventilation for Acceptable Indoor Air Quality (ASHRAE 1989), is a consensus standard that has two procedures for demonstrating acceptable IAQ. One procedure involves assessing whether ventilation rates conform with tabulated values; the other entails measuring contaminants to show that they are below specified levels. The work we report here is part of our ongoing research effort relative to IAQ in offices and has two general goals. Our scientific and technical goals were to assess practical implications of this ASHRAE standard and relationships between its two procedures. Our industrial hygiene goal was to obtain baseline information that can be used to address IAQ concerns in the future.

EXPERIMENTAL

Each of the four buildings was investigated during the working hours of one week in the summer of 1991. Smoking is unrestricted at Buildings A and B. At Buildings C and D, smoking is restricted to lounges where air is exhausted directly to the outdoors. None of the buildings had a history of IAQ problems. Tables 1a and 1b summarize characteristics of the buildings; Table 2 provides information on their HVAC systems. For Buildings A and C, private offices make up most of the floor area. For Buildings B and D, open office areas represent most of the floor area. In terms of age, size, occupancy, floor plan, and HVAC system, each pair of buildings was similar. At each building, one HVAC system and one floor served by that system were investigated. Selection of HVAC system and floor for testing at Buildings A and B was based upon maximal occupancy. The management of Buildings C and D selected HVAC systems and floors to be investigated that were representative of the buildings. At all buildings, occupants of floors tested were mostly clerical personnel and middle managers.

Contractors did all testing with the exception of (1) analyses for particulate substances and (2) monitoring of

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TABLE 1a
General Information on Four Buildings Investigated

Building	Year Occupied	Total number of floors	Total area of building (ft^2)	Number of Occupants (approx.)	Area of test (ft^2)	Number of Occupants in test space
A	1929	22	313,995	680	16,329	66
B	1982	16	471,000	1,400	27,801	114
C	1957	12	477,532	1,433	38,392	15
D	1990	10	570,000	1,000	32,000	54

TABLE 1b
General Information on Four Buildings Investigated

Building	Year Occupied	Total number of floors	Total area of building (m^2)	Number of Occupants (approx.)	Area of test (m^2)	Number of Occupants in test space
A	1929	22	29,170	680	1,516	66
B	1982	16	43,755	1,400	2,582	114
C	1957	12	44,362	1,433	3,566	15
D	1990	10	52,953	1,000	2,972	54

ventilation rates at Buildings B and D. On Mondays, HVAC systems were visually inspected to evaluate design, operation, and maintenance. Temperature and relative humidity were measured to assess thermal comfort. The fraction of outdoor air in the total air supplied to the test floors was quantified based on pitot tube measurements of volumetric flow rates. For VAV systems, the fraction of outdoor air and the total supply to each test floor were continuously monitored. Volumetric flow rates of air supplied by induction units of CAV systems were quantified based on use of empirical calibration curves relating volumetric flow rate to plenum pressure for given types of induction units.

On Tuesdays through Fridays, air samples were collected at randomly selected, occupied office spaces and in breathing zones. The numbers of offices sampled were 20 each for Buildings A and B, 14 for Building C, and 16 for Building D. For comparison with the samples collected in the offices, samples were collected daily from outside air and return air plenums.

RSP and UVPM were determined by the method described by Conner et al. (1990) with the inertial impactor separating at 2.5 μm. The method described by Ogden et al. (1990) was used to determine FPM. Nicotine and VOCs were determined by EPA Method IP-2A (Winberry et al. 1989a) and EPA Method IP-1B (Winberry et al. 1989b), respectively. Samples for RSP, UVPM, FPM, nicotine, and VOCs represented approximate seven-hour integrated averages. Formaldehyde was determined by NIOSH Method 3500 (NIOSH 1984) with samples collected for approximately one hour at the end of each day. CO_2 was determined with an NDIR analyzer. CO, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) were assessed with monitors employing electrochemical sensors. Ammonia (NH_3) and ozone (O_3) were screened with detector tubes. CO_2, CO, SO_2, NO_2, NH_3, and O_3 were sampled daily at three evenly spaced times with the average result used to represent an approximate seven-hour exposure.

A questionnaire was administered to occupants of Buildings A and B. The questionnaire was derived from those published by NIOSH (1987) and the Danish Building Research Institute (DBRI 1990). The questionnaire asked for information on symptoms experienced during the

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TABLE 2
HVAC Systems Serving Four Buildings

Building	Age of HVAC Systems (years)	Systems
A	35	39 fan-coil systems 1 induction systems (induction unit system has no return air capability)
B	10	2 cooling air handlers 2 heating air handlers 1 make-up air unit
C	36	6 peripheral systems 6 interior induction unit systems 26 air handlers
D	1	central fan section for AC/heating (1 for interior, 1 for exterior) 32 cooling zones 10 heating zones

previous three months including four strongly related to IAQ factors: (a) "itching, burning, or irritation of the eyes"; (b) "irritated, stuffy, or runny nose"; (c) "hoarse, dry throat"; and (d) "cough" (DBRI 1990). Smoking prevalence was quantified from responses to the questionnaire. Smoking rates were assessed by collecting and counting cigarette butts. Numbers of occupants were obtained from daily records of attendance.

RESULTS AND DISCUSSION

Inspections indicated that all systems were adequately designed, operated, and maintained. Relative humidities and temperatures for all test spaces ranged from 41% to 65% and 68°F to 78°F, respectively.

All four systems provided ventilation rates (in terms of cfm outdoor air per occupant) essentially conforming to *ASHRAE 62-1989*. For Buildings A and C, which have induction CAV technology, ventilation rates were 106 and 170 cfm (3.00 and 4.81 m^3/min)/occupant, respectively. Figures 1 and 2 show typical daily ventilation rates for Buildings B and D, respectively. At Building B, the average ventilation rate was 17 cfm (0.48 m^3/min)/occupant; ventilation rates varied from 12 to 21 cfm/occupant (0.33 to 0.59 m^3/min). Within the experimental constraints of this investigation, the -3 cfm (-0.08 m^3/min)/occupant average difference relative to the standard is considered negligible. The ventilation rate at Building D averaged 28 cfm (0.79 m^3/min)/occupant and ranged from 21 to 32 cfm (0.59 to 0.90 m^3/min)/occupant. The maximal CO_2 concentration

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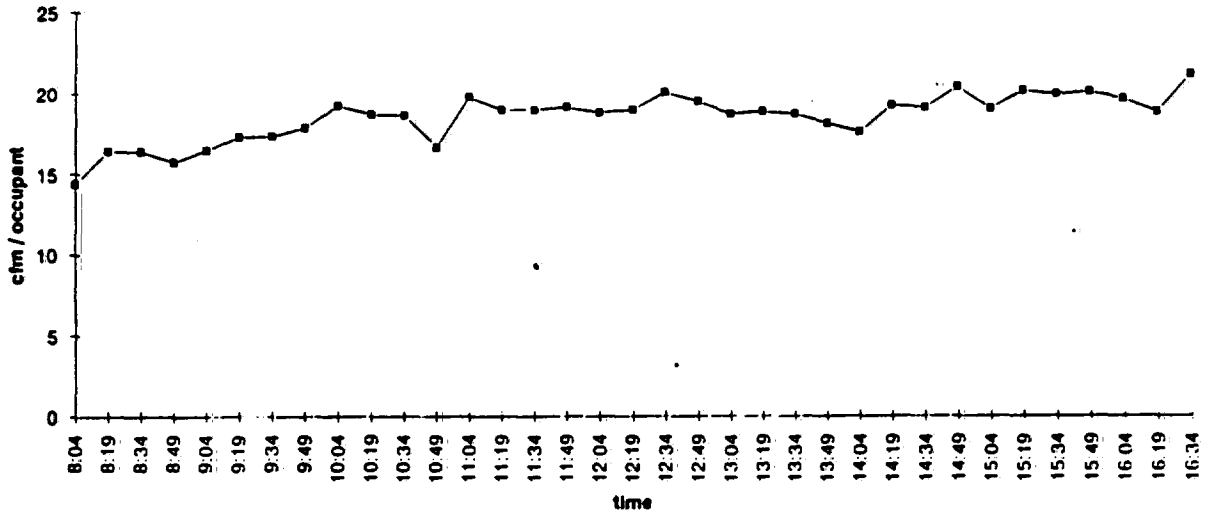

Figure 1 Ventilation rates for the test floor of Building D on July 10, 1991.

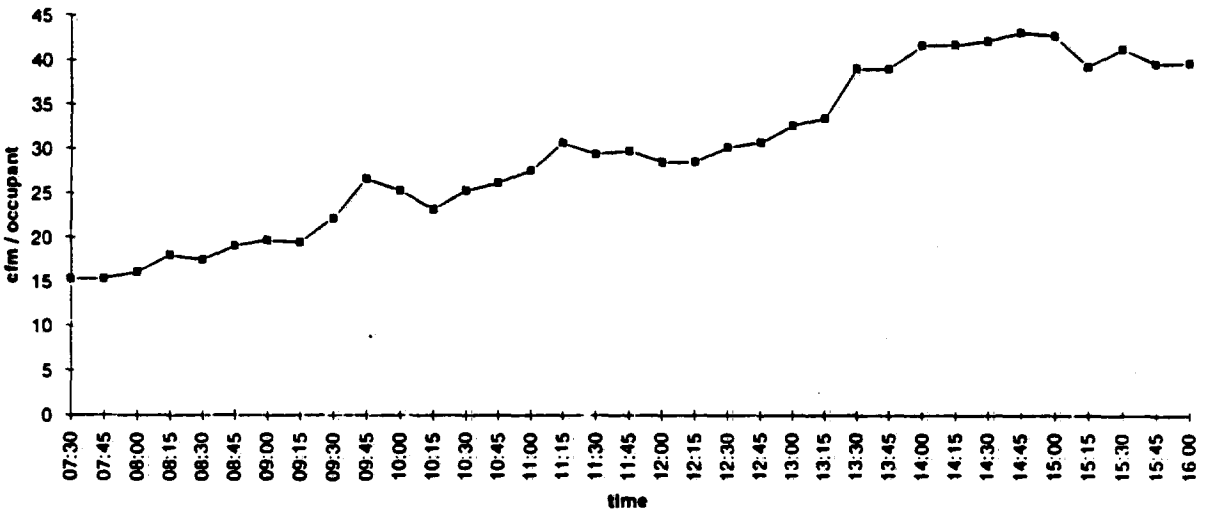

Figure 2 Ventilation rates for the test floor of Building B on July 31, 1991.

for the four buildings was 642 ppm, a result that supports the conclusion that ventilation was adequate.

At Buildings A and B, respectively, fractions of smokers as determined by questionnaire were 37.0% and 33.0%; the numbers of occupants responding were 65 and 121. The prevalence of smoking for both buildings, 34%, is substantially greater than the U.S. average, 28% (CDC 1991). Tables 3 and 4 present data on smoking activity for the two buildings. These data give an average smoking rate of 12.2 cigarettes per smoker per workday. Assuming that smoking occurred during the normal 7½-hour workday at the two buildings gives a smoking rate of 1.6 cigarettes per smoker per hour. This level of smoking activity is 18% less than the estimated U.S. average of two cigarettes per smoker per hour (NRC 1986).

To facilitate discussion, results from determinations of indicators of air quality are addressed relative to respective limits of detection (LODs) and limits of quantitation (LOQs), where the LOQ as used here is defined as three times the LOD. Of the 38 substances sampled, 24 were above limits of detection (LOD). Table 5 lists the 14 substances that were not detected and respective LODs. Of the 24 substances above LODs, four had medians below LODs for every building. (Because many data sets have substantial numbers of data below LODs, median values are used here for summarizing results. Medians, unlike avera-

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TABLE 3
Smoking Activity at the Test Floor of Building A

	DAY			
	Tues	Wed	Thurs	Fri
Number of cigarette butts	277	263	355	224
Number of occupants	53	51	52	50
Number of smokers	21	20	21	20
Number of nonsmokers	32	31	31	30

TABLE 4
Smoking Activity at the Test Floor of Building B

	DAY			
	Tues	Wed	Thurs	Fri
Number of cigarette butts	409	412	412	426
Number of occupants	110	108	108	108
Number of smokers	36	36	37	36
Number of nonsmokers	74	72	71	72

ges, do not depend on the convention used to assign a numerical value to data below LODs.) Chloroethane was quantified once at 15 $\mu g/m^3$ in Building C. Chloroform was detected in nine of the samples from Building B; the range of concentration was from 0.9 to 1.2 $\mu g/m^3$. Naphthalene was detected once at 1.3 $\mu g/m^3$ in the Building B and four times in Building C; for the latter, the range of concentration was from 0.9 to 1.4 $\mu g/m^3$. Finally, 1,1,2-trichloroethane was detected once at 1.5 $\mu g/m^3$ in Building D.

Table 6 presents medians and ranges for the remaining 20 substances found above LODs in offices at the buildings. Four have medians below LOQs; these are CO, formaldehyde, 4-methyl-2-pentanone, and styrene. CO is noteworthy because some researchers have used it as an indicator of ETS. Although the quality of the CO results here is limited because the monitor was accurate to ± 2 ppm, the results are, nonetheless, in line with the position that CO is not a reliable ETS indicator because of its poor selectivity (Guerin et al. 1992). The highest level of CO, 3.0 ppm, was found at Building D where smoking was restricted to lounges exhausted directly to the outdoors. Much of this CO presumably came from outdoor sources, since the average concentration of CO in the outdoor air supplied to the offices was 2.0 ppm.

TABLE 5
Substances below Limits of Detection at All Buildings
(concentrations in $\mu g/m^3$ unless otherwise indicated)

Substance	Limit of Detection
Ozone	0.01 ppm
Ammonia	0.1 ppm
Sulfur dioxide	1.5 ppm
Nitrogen dioxide	1.5 ppm
Carbon disulfide	0.8
Carbon tetrachloride	0.8
Chlorobenzene	0.8
Chloromethane	1.6
1,1-Dichloroethane	0.8
1,2-Dichloroethane	0.8
Isopropyl ether	0.8
Methyl *t*-butyl ether	0.8
1,1,2,2-Tetrachloroethane	0.8
Vinyl chloride	1.7

For purposes of discussion, substances above LOQs can be placed in two categories based upon whether or not they were found only indoors. (Having been addressed above, results for CO_2 are not addressed further here.) Four substances found only indoors were 1,4-dichlorobenzene, trichloroethene, 2-butanone, and nicotine. Nicotine was found only at Buildings A and B where unrestricted smoking occurred. This was expected since nicotine is an indicator of ETS. Interpreted strictly, however, the presence of airborne nicotine indicates only that smoking has occurred (Nelson et al. 1990).

Eleven substances were found both indoors and outdoors: RSP, UVPM, FPM, benzene, ethylbenzene, toluene, xylenes (all three isomers), methylene chloride, tetrachloroethene, 1,1,1-trichloroethane, and trichlorofluoromethane. These can be grouped as particulate species (RSP, UVPM, and FPM), arenes (benzene, toluene, ethylbenzene, and

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TABLE 6
Summary of Results for Determinations of Substances in Office Spaces at Concentrations Greater than Limits of Detection
(medians and ranges in $\mu g/m^3$ unless indicated otherwise; medians greater than LOQ indicated by asterisk [*])

	Building			
Substance	A	B	C	D
CO^2 (ppm)	500*	604*	484*	575*
	(433-575)	(558-620)	(333-542)	(533-642)
CO (ppm)	1.3 ppm	<1.0	2.0	2.4
	(0.7-2.0)	(<1.0-1.0)	(2.0-2.7)	(1.3-3.0)
Formaldehyde (ppm)	0.027	0.034	0.018	0.033
	(0.0085-0.041)	(0.024-0.047)	(0.012-0.020)	(0.030-0.040)
RSP	34*	30*	7	5
	(<7-74)	(<15-48)	(<9-20)	(<8-21)
UVPM	26*	16*	0.8	2*
	(<5-56)	(5-34)	(<1-2)	(0.4-4)
FPM	15*	14*	0.2	1*
	(2-30)	(3-31)	(<.2-0.4)	(0.2-2)
Nicotine	1.8*	2.3*	<0.2	<0.1
	(0.1-11.7)	(0.3-9.9)	(<0.2)	(<0.1)
Benzene	2.1	4.8*	3.5*	1.7
	(0.8-4.4)	(3.7-7.6)	(2.7-4.9)	(1.4-3.6)
2-Butanone	<1.8	5.6*	<1.8	2.6*
	(<1.8-6.0)	(<2.2-14.0)	(<1.8-3.6)	(<1.6-3.4)
1,4-dichlorobenzene	<0.8	4.2*	<0.9	<0.8
	(<0.8-2.0)	(<0.9-5.3)	(<0.9)	(<0.8)

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TABLE 6 (Continued)
Summary of Results for Determinations of Substances in Office Spaces
at Concentrations Greater than Limits of Detection
(medians and ranges in $\mu g/m^3$ unless indicated otherwise; medians greater than LOQ indicated by asterisk [*])

Substance	Building A	B	C	D
Ethylbenzene	1.1	3.0*	1.6	1.6
	(0.9-2.2)	(<0.9-4.0)	(<0.8-3.6)	(1.4-3.0)
4-Methyl-2-pentanone	<1.8	1.7	<1.8	1.2
	(<1.8)	(<2.2-8.6)	(<1.8-3.3)	(0.9-2.1)
Methylene chloride	<0.8	<1.1	<0.9	8*
	(<0.8-7.1)	(<1.1-6.3)	(<0.9-1.2)	(<0.8-23.0)
Styrene	<0.9	1.9	<0.9	0.8
	(<0.9-1.3)	(1.6-2.5)	(<0.9)	(<0.8-1.0)
1,1,2,2-tetrachloroethylene	1.5	2.2	1.4	2.6*
	(<0.9-3.4)	(1.4-2.8)	(1.2-1.8)	(1.5-5.4)
Toluene	9.5*	19*	12*	21*
	(4.7-17)	(17-27)	(8.6-21)	(17-62)
1,1,1-trichloroethane	18*	50*	46*	29*
	(4.9-73)	(39-71)	(25-58)	(13-76)
Trichloroethene	2.8*	8.2*	2.9*	5.8*
	(<0.8-16)	(6.3-14)	(2.4-4.8)	(4.1-8.3)
Trichlorofluoromethane	1.2	1.2*	<0.9	5.2*
	(<0.8-1.8)	(<0.9-29.0)	(<0.9)	(3.9-7.1)
Xylenes	4.9*	12.0*	7.9*	6.0*
	(<0.8-9.1)	(2.6-16.0)	(5.8-16.0)	(4.7-11.0)

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xylenes), and chlorinated hydrocarbons (methylene chloride, tetrachloroethene, 1,1,1-trichloroethane, and trichlorofluoromethane).

Levels of RSP, UVPM, and FPM were higher for Buildings A and B than for Buildings C and D. For RSP, this difference reflects, in part, differences in outdoor levels of RSP. At Buildings B, C, and D, indoor levels of RSP were not statistically different from outdoor levels ($P > 0.05$). For Buildings C and D, median concentrations of RSP indoors and outdoors were the same. At Building B, the median outdoor level of RSP was 26 $\mu g/m^3$. RSP, because of its lack of selectivity and sensitivity, is a relatively poor indicator of particulate matter from ETS. Based on degree of selectivity and sensitivity, UVPM is better and FPM is the best of the three indicators of particles from ETS (Ogden et al. 1990). Based on FPM results, the estimated contribution of particles from smoking in Buildings A and B is about 15 $\mu g/m^3$.

The arenes are associated with products of combustion, solvents, and motor fuels. The presence of arenes both indoors and outdoors is expected, especially since all four buildings are located in urban areas. Indoor levels of arenes are at essentially the same magnitude for all four buildings.

The chlorinated hydrocarbons are associated with solvents, dry-cleaning operations and residues on clothing, and refrigerants (trichlorofluoromethane only).

Table 7 summarizes responses (by symptom) to the questionnaire for Buildings A and B. Response rates for the questionnaire were 87.9% at Building A and 91.7% at Building B. Response rates for symptoms are computed relative to the number of questionnaires returned. Rates for symptoms range from 1.7% (for "Cough" at Building A) to 19.0% (for "Itching, burning, or irritation of the eyes" at Building A). In general, rates at Building A are much greater than those at Building B.

Although the questionnaire was not designed to address acceptable IAQ per se, it can be used for this purpose by assuming that the converse of the criterion within *ASHRAE 62-1989* is applicable:

> The air can be considered acceptably free of annoying contaminants if less than 20% of a panel of at least 20 untrained observers deems the air to be objectionable under representative conditions of use and occupancy ... .

Application of this criterion to the individual response rates shown in Table 7 implies that IAQ was generally acceptable at both buildings.

At the four buildings, levels of all contaminants were within respective standards used for industrial hygiene applications. Relative to standards for VOCs, benzene reached the highest level. The maximal concentration of benzene, 7.6 $\mu g/m^3$, is more than four orders of magnitude below the ACGIH (eight-hour time weighted average) threshold limit value (TLV) of 32 mg/m^3 (ACGIH 1990). All levels of formaldehyde are below both federal and state standards as tabulated in Appendix C of *ASHRAE 62-1989*. The largest concentration of CO was 3.0 ppm; this value is below both the ACGIH TLV of 50 ppm and the eight-hour average of 9 ppm recommended in the ASHRAE standard.

TABLE 7
Summary of Responses to Categories of Symptoms

Symptom	Building A		Building B	
	%	Number	%	Number
Itching, burning, or irritation of the eyes	19.0	11	7.2	8
Irritated, stuffy, or runny nose	15.5	9	8.1	9
Hoarse, dry throat	10.3	6	5.4	6
Cough	1.7	1	2.7	3

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In addition, levels of RSP are below levels suggested by the ASHRAE standard. The greatest concentration of RSP (measured in the private office of a smoker) was 74 $\mu g/m^3$. Based upon averaging time, the most appropriate standard for interpreting this approximate seven-hour exposure is the 24-hour average, primary National Ambient Air Quality Standard of 150 $\mu g/m^3$.

Results indicate that the smoking lounges at Buildings C and D were effective at preventing dispersal of smoke to offices on the same floor. The tobacco-selective contaminants, nicotine, UVPM, and FPM, were either below the LOD (as was the case for nicotine) or at background levels determined in the outdoor air. These results are expected based upon two facts. First, air from both lounges is exhausted from each building rather than being recirculated. Second, results from assessments of ventilation with smoke tubes showed that the lounges were at a pressure slightly negative relative to adjacent occupied spaces on the floor.

CONCLUSIONS

Investigations of indoor air quality in two buildings where smoking was unrestricted and two buildings where smoking was restricted to lounges showed:

1. In these buildings, with the HVAC systems adequately designed, operated in accordance with the current ASHRAE standard, and properly maintained, all indicators were well within applicable standards, regardless of the smoking policy.
2. Smoking activity had a negligible effect, in general, on contaminant levels in buildings where smoking was unrestricted. Although levels of some contaminants were higher than those in the buildings where smoking was restricted, all contaminants measured were within applicable standards.
3. Restricting smoking to lounges eliminated nonsmoker exposure to ETS by preventing smoke from dispersing to adjacent areas. No tobacco-selective contaminants were indicated in office spaces on the same floor tested.
4. Smoking was associated with increased indoor levels of respirable suspended particles (RSP), but these increases were small with ventilation rates conforming to the current *ASHRAE 62-1989*. RSP levels were all within accepted standards in all four buildings during all tests.

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